Selection of Exploitation Method Based on the Experience of Hydraulic Fracture Techniques at the El Teniente Mine

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ABSTRACT

The exploitation of primary ores using cave mining caused new challenges at the El Teniente mine that required changes to a number of conventional cave mining practices. For example, in the 1970s and 1980s, panel caving was introduced to manage certain geotechnical and operational conditions. Today, El Teniente mine is facing new challenges associated with deep cave mining and establishing its New Mine Level (NML) project, which is located 240 m below the Esmeralda operating cave.

The engineering and development phases for this new project have been largely based on experience and lessons learned throughout the history of primary ore exploitation at El Teniente mine, particularly knowledge about seismicity control, the management of collapses and operational practices. For example, previous experience demonstrated that seismicity could be managed by preconditioning using large-scale hydraulic fracturing (HF). HF has been systematically applied in the column of ore above the undercut planned for the NML project and below the production or extraction level, where the main ventilation and haulage infrastructure are to be located.

This paper discusses how this has been achieved and is based on previous experience of preconditioning using HF, which has been applied in the selection and management of exploitation techniques and associated planning strategies and design parameters for the NML project.

INTRODUCTION

El Teniente mine overview

The exploitation of primary ore at Codelco's El Teniente mine started in 1982 (Figure 1). The ore rock encountered had lower average and stronger grades, resulting in coarser fragmentation reporting to drawpoints compared to the secondary ores, which were also being mined at the time. Load-haul-dump vehicles were then introduced to extract and move ore or course fragmentation from the drawpoints to ore collection points. This was the main difference to the conventional block caving method. Other differences included an increase in block height, larger open areas to draw from and the systematic incorporation of caved areas (dynamic caving front). This all occurred in a high-stress and complex geological environment, which resulted in stability issues. These were new to the operation, and included slabbing of tunnel walls, excavation overbreak, structural collapses and rock bursts.

In addition to the implementation of the panel caving variant of block caving, a number of studies, controls and tests have since been conducted in-house, mainly of a geomechanical nature, to respond to the large number of questions that were being asked about the stability of drifts mined in primary rock.

LESSONS LEARNED FROM EXPLOITATION OF PRIMARY ORE

Conceptualisation of cave propagation phases (breakthrough, connection and regime phases)

Based on empirical evidence and fundamental engineering principles used in the El Teniente 4 Sur and El Teniente Sub 6 operations, a conceptual model was developed that enabled the successful mining of primary ore. For example, low draw rates enabled the re-adjustment of the rock mass (ie stress redistribution), preventing strain increases that caused larger rock failures. The empirical evidence and conceptual model demonstrated that cave initiation represented the greatest risk associated with the caving method. The same experience demonstrated that once the propagating cave connected with the surface or the depleted caves above, it would result in more favourable, steady-state caving conditions (Rojas *et al*, 2000).

Experimental mining at the El Teniente Sub 6 operation established a relationship between seismicity and the rate of ore extraction. This relationship enabled better management and control of seismicity and a reduction in the likelihood of rock burst occurrences.

Seismic activity is the way that the rock mass responds to the mining method being employed. In this instance, it involves

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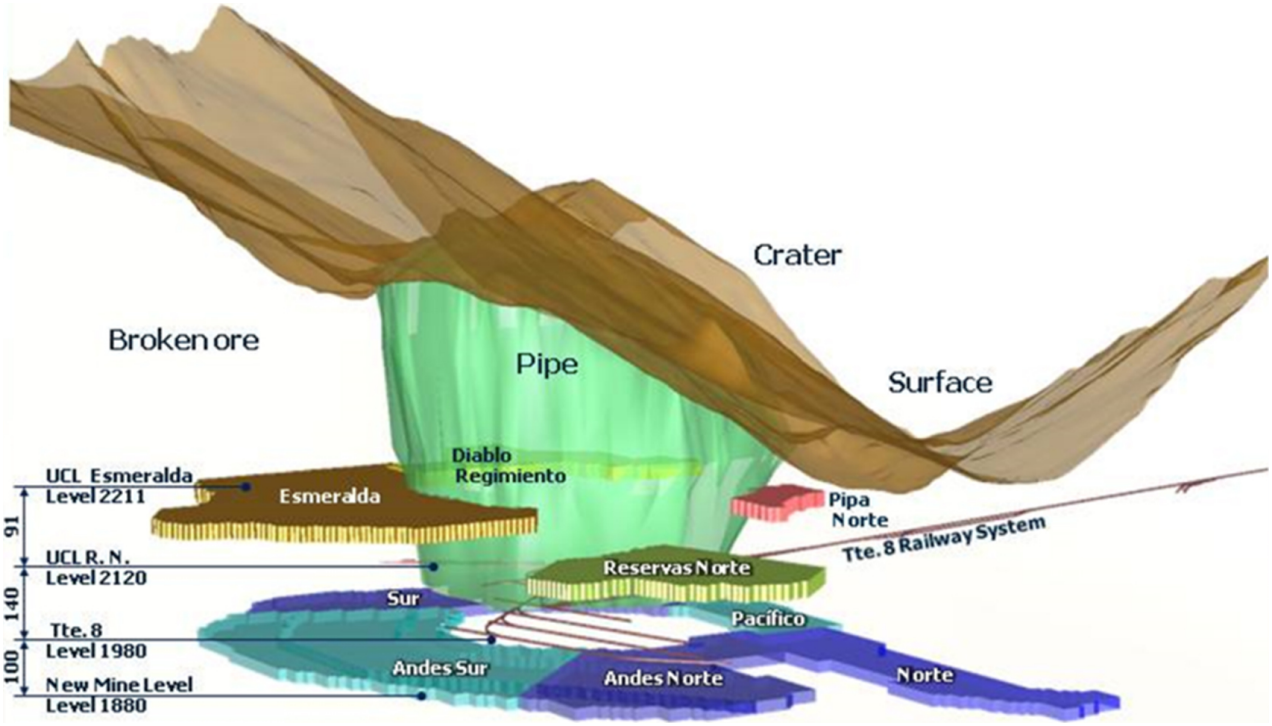


FIG 1 – Productive sectors and projects, El Teniente mine.

how the caved area is incorporated and the development of the draw strategy. This feedback from the rock mass can be used to develop criteria and parameters for the mine planning process.

Implementation of hydraulic fracturing

Hydraulic fracturing (HF) is used to systematically generate an array of artificially induced fractures that ultimately modify the rock mass condition, thereby reducing seismic hazards and enhancing cavability. Experience from operations such as Reservas Norte, Esmeralda and Diablo Regimiento has clearly shown that the magnitude of the maximum expected event does not exceed 1.5 in the volume of preconditioned rock (Parraguez, Zepeda and Rojas, 2009). This has been statistically confirmed by experience at Reno, where an assessment of the effect of preconditioning on the seismic hazard compared the largest event (Figure 2) both before and after preconditioning. The maximum event showed a significant reduction after preconditioning. Although the time periods before and after are completely different, the periods were characterised by similar undercutting and draw rate and the same geotechnical condition.

Ground support systems

During the 1980s and early 1990s, radical changes took place in the reinforcement elements and systems used at El Teniente mine. This evolution was conceptualised and put into practice at El Teniente 4 Sur operation with the aim of developing support systems that would enhance energy-absorption capacity to keep rocks from dynamic failures.

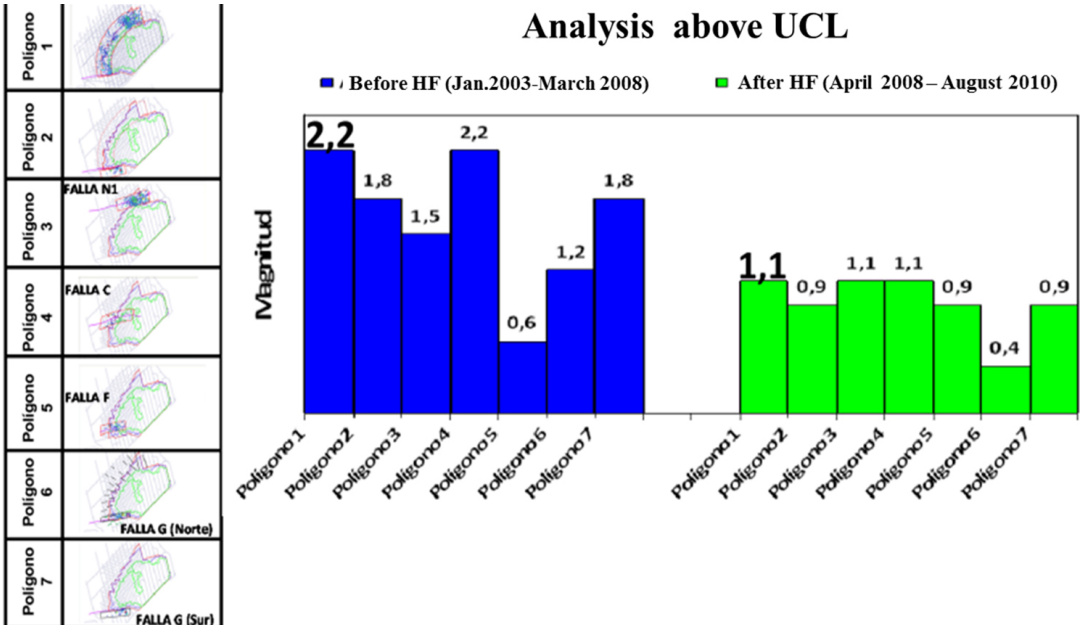


FIG 2 – Results showing the reduction in the maximum seismic event experienced at Reno after the preconditioning campaign (Zepeda *et al*, 2011).

The new elements and systems put in place improved the capacity to contain rock projected from rock bursts. This improvement translated into the eradication of minor injury events, which, in turn, reduced the total number of rock bursts (see Figure 3).

The main lesson learned was that a support system must be taken into account, the type of failure, identifying potential seismicity sources and attenuations from the environment (Rojas and Cavieres, 1993).

Variants of exploitation methods

Table 1 provides a schematic summary of the historic evolution experienced by the exploitation variants implemented at El Teniente mine, mainly during the primary ore exploitation period. The key factors that characterise each implemented variant are identified, together with the factors that eventually became critical to determining its successful application.

ASSESSMENT OF THE EXPLOITATION METHOD FOR THE NEW MINE LEVEL PROJECT

Geotechnical characterisation

Figure 4 shows the geotechnical zoning (domains) of the New Mine Level (NML) project (elevation 1880 m) undercut level. This characterisation is mainly based on the current criteria established by the geology group at El Teniente mine regarding the existence of weak discontinuities (soft veinlets and faults) that, in general, make a differentiation on the Fw (east) and Hw (west) sides of the rock mass (Brzovic, Pereira and Schatcher, 2014). Considering this, veinlet frequency (fv/m) on the Fw side ranges between 7.5 and 9.0 fv/m, while it ranges between 2.0 and 4.0 fv/m on the Hw side.

By interpreting the results obtained from 3D numerical models (Software Map 3D and Abaqus) employed at El Teniente, a zoning based on the distribution of the major principal stress (σ1) has been established. Figure 5 represents this, showing a stress distribution with expected premining stress state for the initial caving area of more than 60 MPa.

A review of exploitation methods for the New Mine Level project

From its prefeasibility studies, the NML project considered the use of panel caving with a crinkle cut advanced undercutting strategy. This decision was based on two key factors:

1. Flat advanced undercutting was being applied in the Reno and Esmeralda operations at the El Teniente mine. Significant undercutting problems were being experienced due to the loss of blastholes in the undercut level (UCL).
2. The crinkle cut variant was being applied with good results at Palabora and Northparkes.

A pilot test was conducted at the El Teniente 4 Sur operation. A significant loss of blastholes in the UCL due to stresses was experienced, which compromised the safety of workers during blasthole charging and muck extraction at the UCL. It was concluded that these operations failed to achieve the design criterion of the project.

Based on this experience, conventional undercutting with HF was selected as the best variant for the NML project.

Conventional undercutting with hydraulic fracturing

Conventional undercutting with HF involves the implementation of HF to reduce seismic hazards and, thus make dynamic stress to generate a milder effect on pillars. An

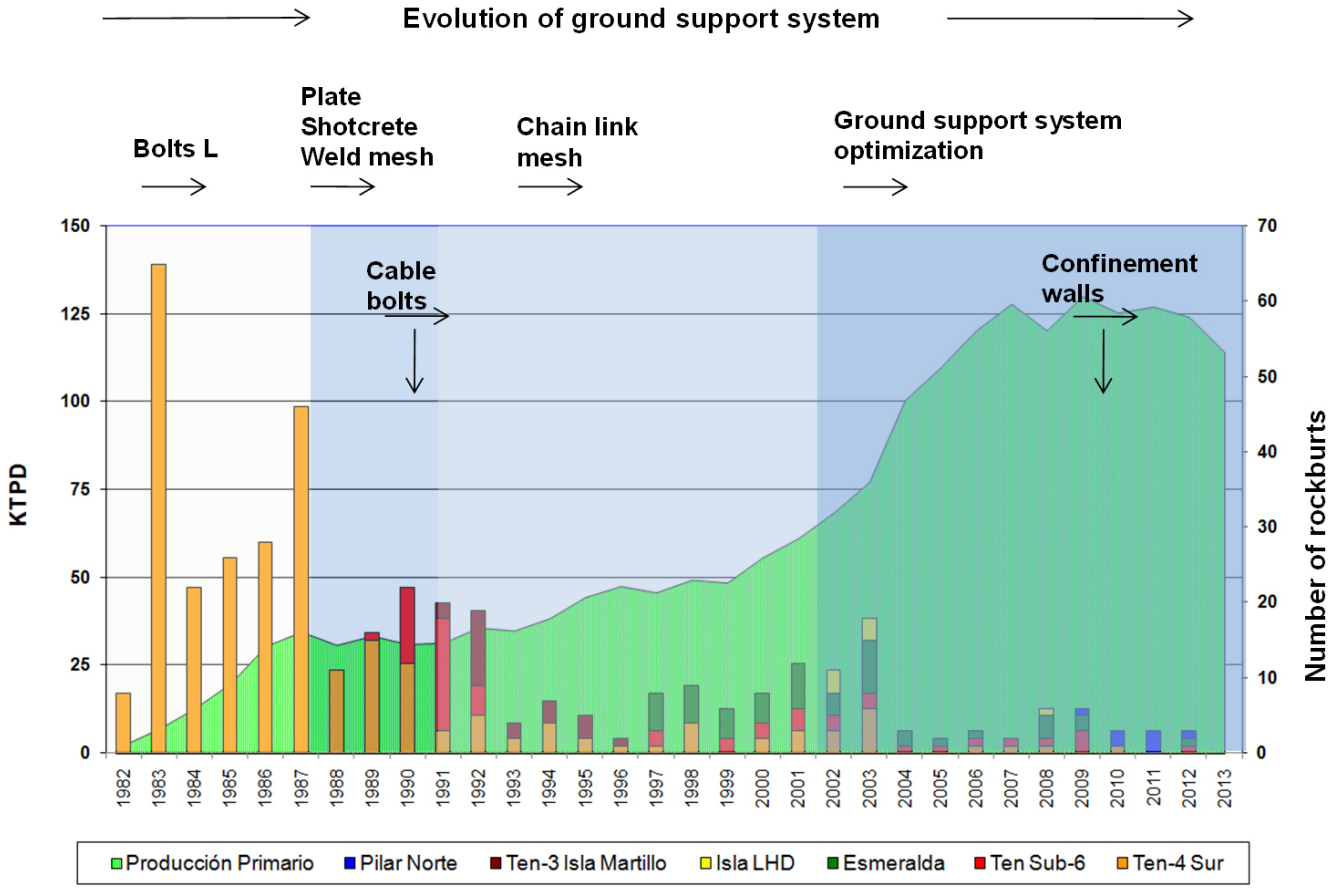
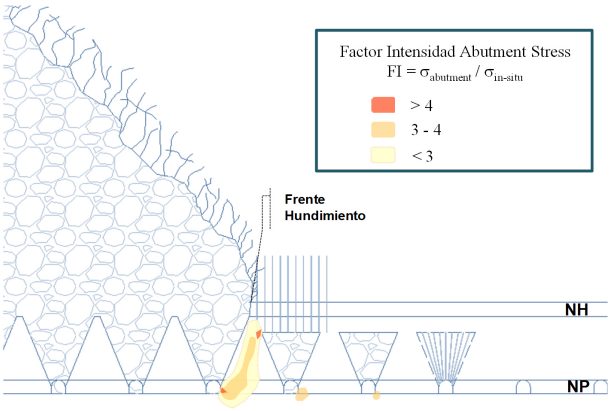
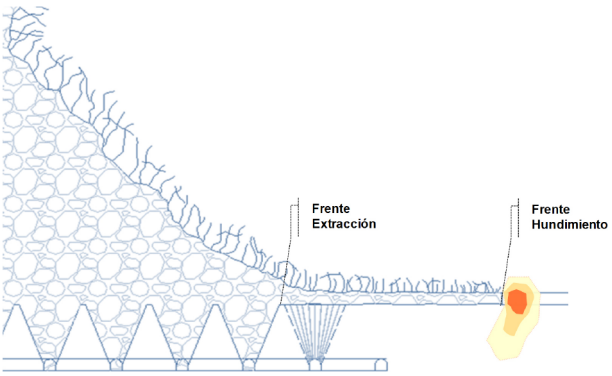
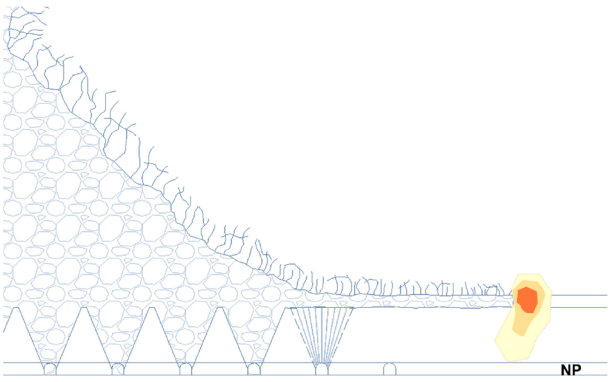
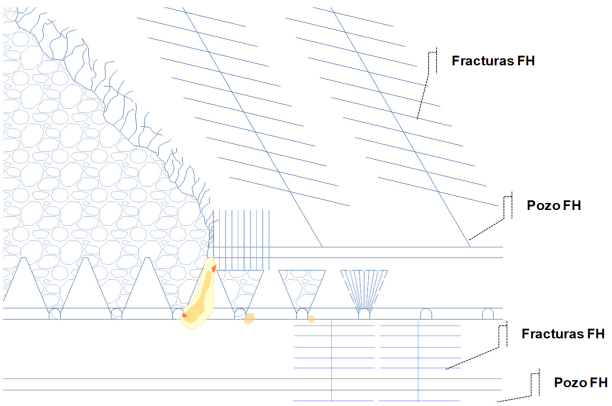


FIG 3 – Systematic evolution of support systems and rock bursts generated at Teniente-4 Sur (Rojas, 2013).

TABLE 1

Evolution of exploitation method for primary ore at El Teniente mine.

Exploitation variant	Critical factors
 **(A)** Panel caving, conventional undercutting (1982–2010).	• The undercutting front is in line with the extraction front and one or two drawbell drift lines are prepared ahead of the caving front with long-haul rings. • The abutment stresses affect a larger volume of rock in the crown pillar with medium-high intensity factor. Thus, drawbell incorporation becomes the most complex operation. • At the beginning of Teniente-4 Sur exploitation, the area availability was compromised by both the rehabilitation of drawpoints and damage in orepasses. This condition was greatly improved with the implementation of new support designs (eg steel rings in orepasses and shotcrete).
 **(B)** Panel caving, preundercutting sequence (1997–2005).	• The undercut front ahead of the extraction front and ahead of the production-level workings. The drawbells are opened up under the undercut zone for both variants. As in case (c), part of the production level is developed ahead of the caving stage (generally, the production drifts). • Low and flat undercutting generate an abutment stress zone ahead of the caving front (highlighted in red) with a very high intensity factor (over four times). Such high stress concentration creates a halo of intense damage around the caving front, which affects undercut drives and the undercut level (UCL) blastholes. • The systematic loss of blastholes in the undercut level has an impact on the undercutting process, resulting in remnant pillars which, in turn, jeopardise the success of the caving process. These remnant pillars transmit the load to production-level pillars, causing extraction-level pillar collapse. • This variant offers very little *flexibility* in terms of operational coordination between preparation and extraction tasks and also in the execution of operational activities to control unexpected stability events in the activation of geological structures at production-level pillars. • This variant makes it difficult to deal with collapse issues due to the lack of production infrastructure ahead of the front.
 **(C)** Panel caving, advanced undercutting sequence (2004–2014).	
 **(D)** Panel caving, conventional undercutting with hydraulic fracturing (2010–2015).	• Massive implementation of hydraulic fracturing (HF) of the rock column to be mined (at least 100 m) as well as in selected areas of the rock mass volume under the production level with the conventional undercutting variant. • The abutment stress has the same characteristics as for the conventional variant. HF reduces the risk of seismic hazards and, in turn, lowers the impact of seismicity-generated *dynamic stresses* on the pillars. • Seismicity is almost exclusively triggered and controlled by the addition of area in production (drawbell opening and undercut blasting), which facilitates the implementation of efficient post-blast re-entry criteria.

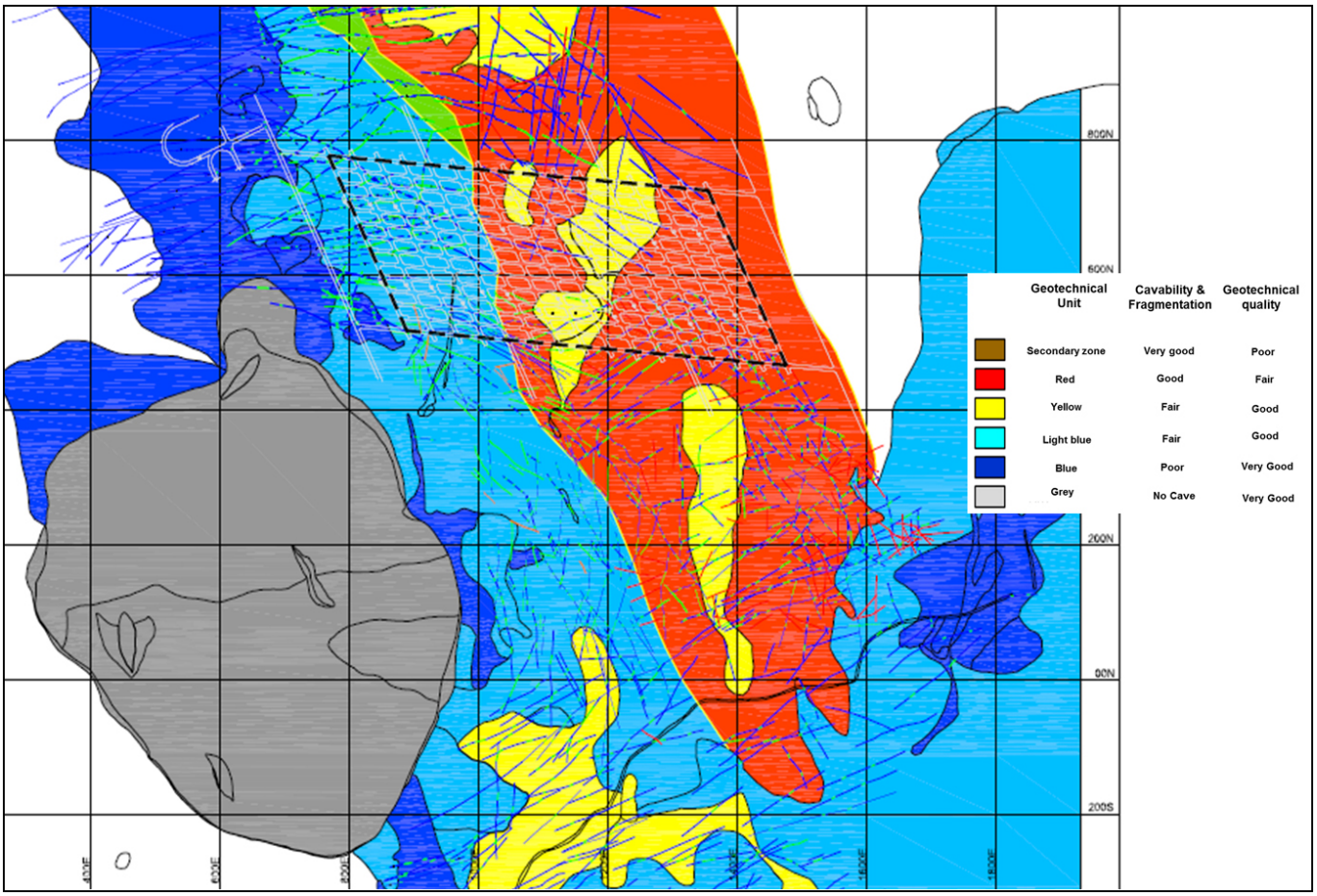


FIG 4 – Diagram of geotechnical zoning in the undercut level at the New Mine Level project (Brzovic, Pereira and Schatcher, 2014).

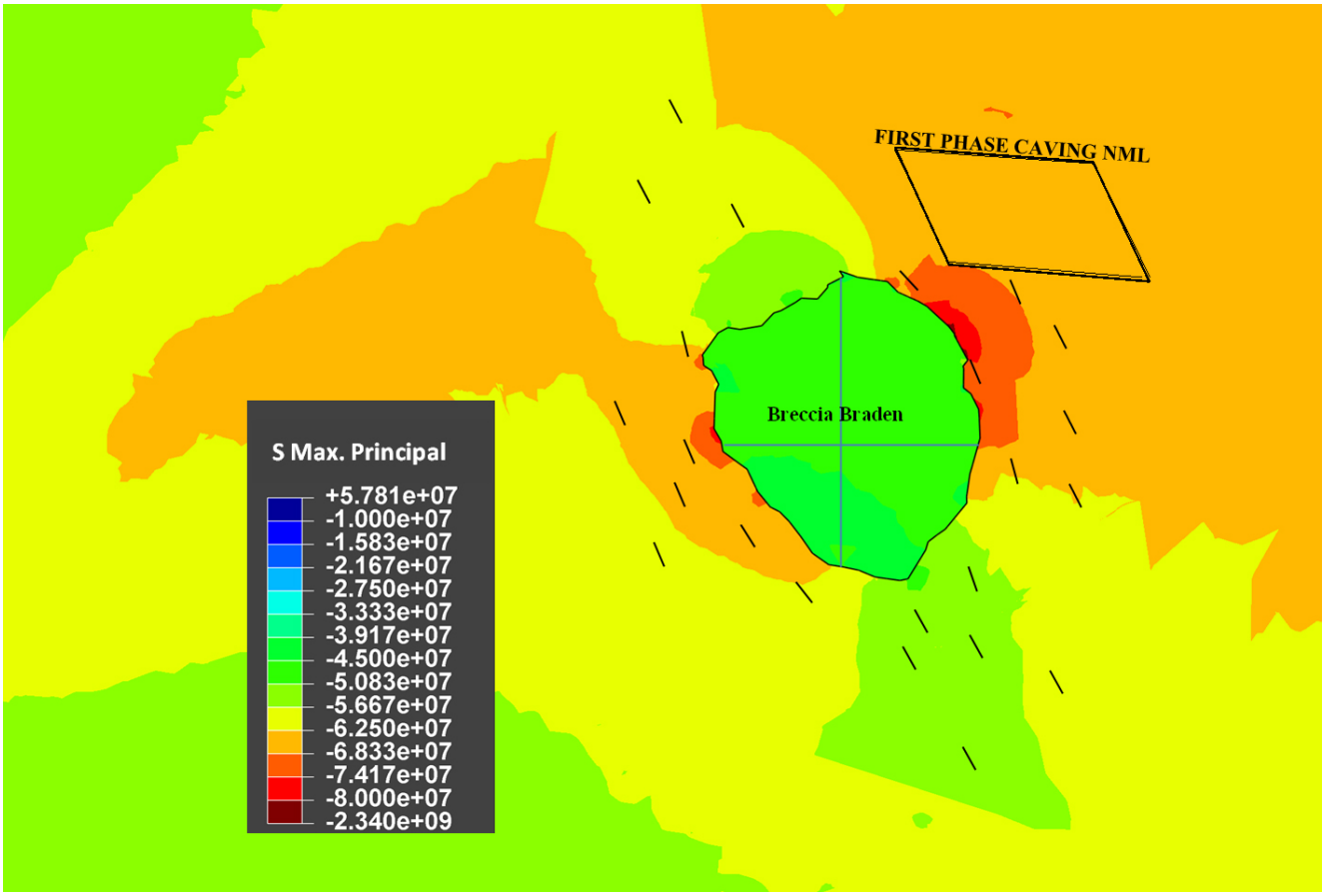


FIG 5 – Major principal stress distribution at the undercut level at the New Mine Level project.

evaluation of the history of HF implementation at El Teniente mine, as described in the *Lessons Learned from Exploitation of Primary Ore* section, has shown this assumption to be true. However, in an effort to also link seismic hazards with the implemented exploitation variants, a comparison was made between two mining realities for the same operation. To that effect, seismic behaviour records for two stages at the Esmeralda mine were reviewed:

1. Traditional Esmeralda – characterised by the implementation of the preundercutting variant
2. Esmeralda Bloque 1 (South) – characterised by the implementation of the conventional undercutting variant with HF.

Figure 6 presents a summary of two representative sections and shows all the seismic activity generated during the two periods analysed. The following are important aspects to note:

1. The preundercutting variant in Figure 6a revealed a higher frequency and large number of events of magnitude above 1.5, with four episodes with a magnitude above 2.6 occurring. This implies more severe seismic hazards, which translate into an increased number of rock burst events. In addition, undercutting, caving initiating and cave back growth can be distinguished. Both the undercutting and the cave back growth processes show the occurrence of events with a magnitude of greater than 2.0 that are close to the production level.
2. The conventional undercutting variant plus HF (Figure 6b) shows a lower frequency of seismic events and associated magnitude in the caving initiation and growth processes. These episodes do not exceed a magnitude of 1.5 in the HF rock volume.

From a production perspective, the exploitation of Esmeralda blocks with conventional undercutting plus HF

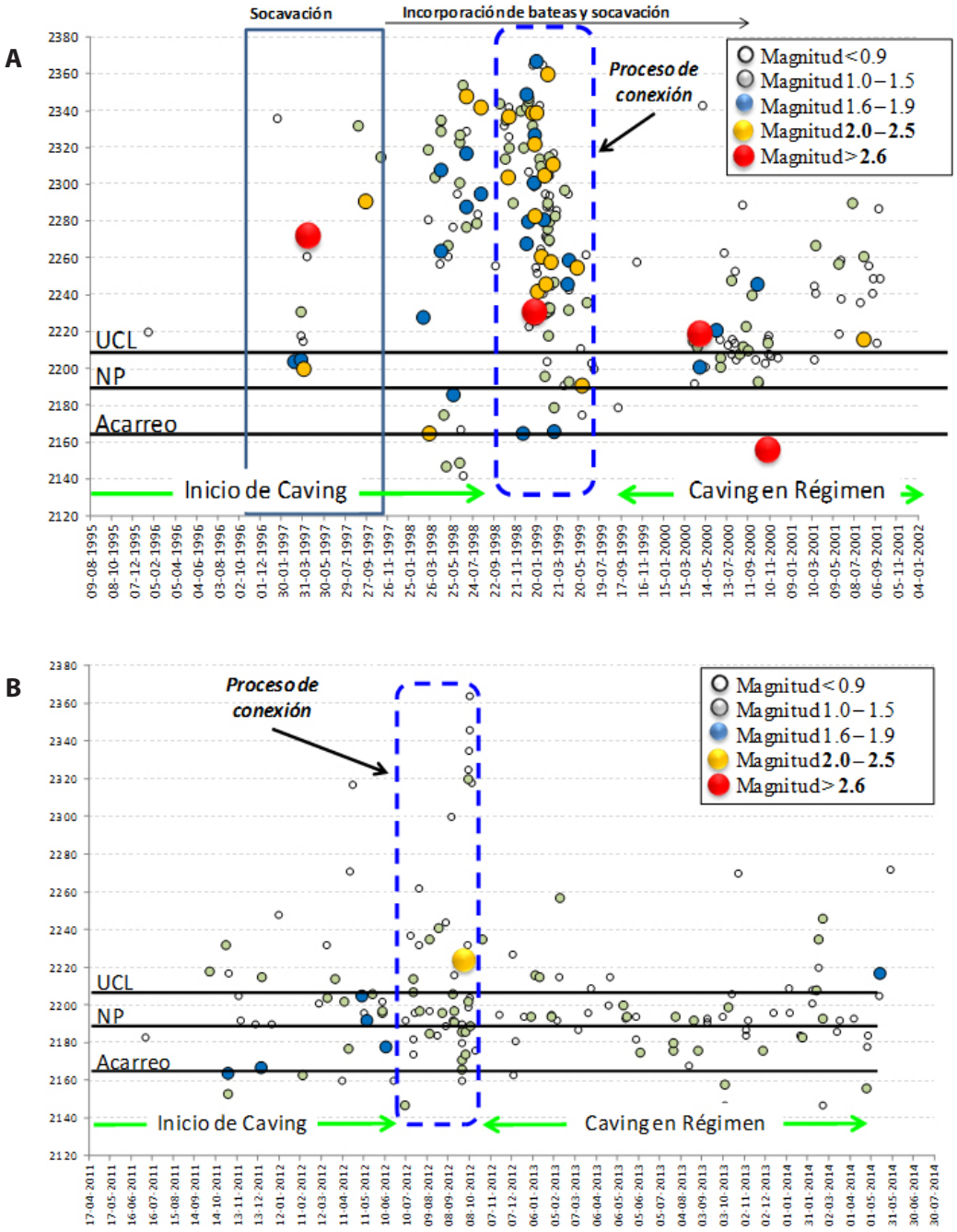


FIG 6 – Vertical section with seismic activity in the Esmeralda sector. (A) Esmeralda Traditional – preundercut without hydraulic fracturing; (B) Esmeralda Bloque 1 – conventional undercutting with hydraulic fracturing (Rojas and Pardo, 2014).

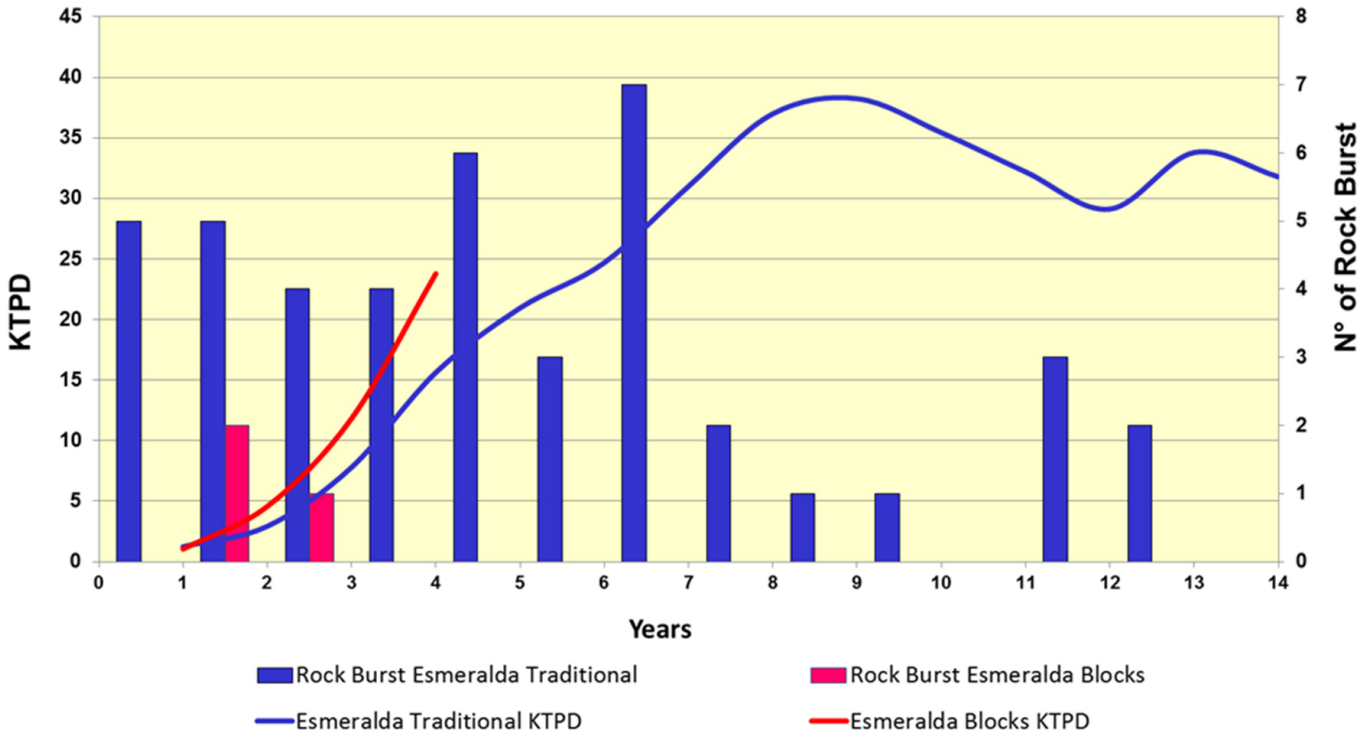


FIG 7 – Primary ore production and number of rock bursts at traditional Esmeralda (preundercutting) and Esmeralda blocks (conventional undercutting with hydraulic fracturing) (Rojas and Pardo, 2014).

delivered a better ramp-up compared to preundercutting and a clearly lower rock burst rate, as shown in Figure 7.

CONCLUDING REMARKS

Based on the information and analyses in this paper, the following can be concluded:

- The NML project has relatively similar geotechnical conditions to those found in the upper levels of the El Teniente mine (ie Esmeralda). However, the stress levels are higher. These conditions make the application of the crinkle cut variant impractical.
- The preconditioning strategy of the NML project needs to incorporate HF, including current industry best practices.
- Conventional undercutting with HF has helped to control seismicity and provides the required flexibility to ensure exploitation continuity in an area. As a result, the implementation of this process is recommended for the conditions expected to prevail at the NML project to ensure that the production commitments stated in the project are fully met.

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